eRHIC
understanding the nuclear initial state with an electron ion collider
hot quarks 2012
tobias toll
our understanding of some fundamental properties of the glasma, sQGP, and hadron gas depend strongly on our knowledge of the initial state!
3 conundrums of the initial state:

1. what is the spatial transverse distributions of gluons?
2. how much does the spatial distribution fluctuate? lumpiness, hot-spots etc.
3. how saturated is the initial state of the nucleus?
is the sQGP a perfect fluid?

IP-Glasma

KLN(CGC)

Glauber Woods-Saxon

AdS/CFT predicts for a perfect fluid: $\eta/s = 1/(4\pi) \sim 0.08$

Schenke, Tribedy, Venugopalan arXiv:1202.6646

$\eta/s=0.08, b=9\text{fm}$

$N_{\text{part}}$

$N_{\text{binary}}$

$p_T [\text{GeV}]$

$v_2$

$v_3$

$v_4$
wouldn’t it be nice if we could measure the initial state directly?
what has been measured?

Hahn, Ravenhall, and Hofstadter, Phys Rev 101 (1956)

electron colliding with fixed ion target, large $x$ charge distribution - no gluons!
what can eRHIC do?
DIS $e\rho$ and $eA$

$e$, $e'$, $\gamma$, $Q^2$, hadrons, $p/A$

Saturday, October 20, 2012
DIS $e p$ and $e A$
**diffraction ep and eA**

**HERA:**
proton collides with electron at CMS energy $\sim 300 m_p$.
in $\sim 15\%$ of measured collisions proton stays intact!

**eRHIC e+A:**
ion predicted to stay intact in 25%-40% of events w. saturation!
diffraction $e+p$ and $e+A$
why is diffraction so great?

diffraction sensitive to gluon momentum distributions$^2$:

$$\sigma \propto g(x, Q^2)^2$$

how does the gluon distribution saturate at small $x$?
eRHIC predictions: inclusive diffraction

can constrain models a lot with a few months of running! already in Stage I!
why is diffraction so great?

depend on \( t \), momentum transfer to proton/ion. Fourier transform of \( t \)-distribution = transverse spatial distribution spatial imaging!
why is diffraction so great?

sensitive to spatial gluon distributions

light scattering elastically off a circular screen of radius $R$

a projectile scattering off a nucleus of radius $R$

-not a ‘black disk’, edge effects

-inelastic scattering

\[ \theta_i \sim \frac{1}{kR} \]

\[ |t|_i \sim \frac{1}{R^2} \]
incoherent Scattering

Good, Walker:

nucleus dissociates \((f \neq i)\):

\[
\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i | A | f \rangle^\dagger \langle f | A | i \rangle \tag{complete set}
\]

\[
= \sum_{f} \langle i | A | f \rangle^\dagger \langle f | A | i \rangle - \langle i | A | i \rangle^\dagger \langle i | A | i \rangle
\]

\[
= \langle i | |A|^2 | i \rangle - |\langle i | A | i \rangle|^2 = \langle |A|^2 \rangle - |\langle A \rangle|^2
\]

the incoherent CS is the variance of the amplitude!!

\[
\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi} \langle |A|^2 \rangle
\]

\[
\frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi} |\langle A \rangle|^2
\]
how to measure $t = (P_A - P'_A)^2$

need to measure $P_A'$

coherent case: $A'$ disappears down beam pipe

incoherent case: cannot measure all beam remnants

only possibility: Exclusive diffraction

$e + A \rightarrow e' + VM + A'$

$t = (P_{VM} + P_{e'} - P_e)^2$
The phenomenon of diﬀraction is familiar to us from many areas of physics and is generally understood to arise from the constructive or destructive interference of wavefronts. One such example is a plane wave impinging on a single slit as shown in Figure 1. In the strong interactions, diﬀractive events have long been interpreted as resulting from scattering of subatomic wave packets via the exchange of an object called the Pomeron, named after the Russian physicist Isaac Pomeranchuk. Indeed, much of the strong interaction phenomena of multiparticle production can be interpreted in terms of these Pomeron exchanges.

In the modern strong interaction theory of Quantum ChromoDynamics (QCD), the simplest model of Pomeron exchange is that of a colorless combination of two gluons, each of which individually carries color charge. In general, diﬀractive events probe the complex structure of the QCD vacuum that contains colorless gluon and quark condensates. Because the QCD vacuum is non-perturbative and because much of previously studied strong interaction phenomenology dealt with soft processes, a quantitative understanding of diﬀraction in QCD remains elusive.

Significant progress can be achieved through the study of hard diﬀractive events at collider energies. These allow one to study hadron final states with invariant masses much larger than the fundamental QCD momentum scale of \( \sim \frac{1}{\sqrt{s}} \) GeV. By the uncertainty principle of quantum mechanics, these events therefore provide considerable insight into the short distance structure of the QCD vacuum.

eRHIC predictions: new physics event generator
sartre

exclusive
diffractive vector
meson and DVCS
production in eA
t. ullrich & t.t.
eRHIC predictions:
sartre dipole model with glauber bSat and bNonSat

Glauber (Woods-Saxon)

Saturday, October 20, 2012
eRHIC predictions: exclusive diffraction with Sartre

Can constrain models a lot with a few months of running!
First 4 dips obtainable.
Probing the spatial gluon distribution at eRHIC

\[ \frac{d\sigma}{dt} = \frac{1}{16\pi} |A(\Delta)|^2 \]

\[ \Delta \sim \sqrt{-t} \]

\[ A(\Delta) \sim \mathcal{F}ourier (\text{Wave Overlap} \cdot \text{Dipole Model}(b)) \]

Fourier transform again to retain spatial distribution:

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mid_{\text{mod}} \]
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty \Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]

Saturday, October 20, 2012
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]

\[ b (\text{fm}) \]

\[ F(b)/\int F(b) \, db \]

---Proving the spatial gluon distribution at eRHIC---

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]

\[ b (\text{fm}) \]

\[ F(b)/\int F(b) \, db \]

---Proving the spatial gluon distribution at eRHIC---
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\left. \frac{d\sigma_{\text{coherent}}}{dt}(\Delta) \right|_{\text{mod}} } \]
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^{\infty} d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}((\Delta))} \mod \]

\[ F(b) / \int F(b) \, db \]

b (fm)
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \left[ \frac{d\sigma_{\text{coherent}}}{dt}(\Delta) \right]_{\text{mod}} \]

Saturday, October 20, 2012
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta J_0(\Delta b) \sqrt{\left. \frac{d\sigma_{\text{coherent}}}{dt} \right|_{\text{mod}}(\Delta)} \]
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_{0}^{\infty} d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mid_{\text{mod}} \]

(a) (b) (c) (d)
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_{0}^{\infty} db \]

\( b_{\text{NonSat}} \propto \text{W.S.} \)

Saturday, October 20, 2012
Probing the spatial gluon distribution at eRHIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod | \]

(a) (b) (c) (d)

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod | \]
Probing the **spatial** gluon distribution at eRHIC

\[
F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \bigg|_{\text{mod}}
\]

---

\(J/\Psi\) is the best suited probe to obtain spatial distribution independent of model!
summary

diffraction in eA is a great tool for measuring:

1. a signal for gluon saturation
2. gluon spatial distribution in nuclei

saturation signal, day 1 measurement via diffractive/total ratio

gluon spatial distributions in nuclei available in a model independent way via exclusive heavy vector mesons, s.a. $J/\psi$

eRHIC truly an ultra high resolution femtoscope for probing the initial state of nuclei
back up
What is being measured?

Coherent Diffraction ($\gamma^* + IP$) in UPC at RHIC

- Coherent diffractive $\rho$ production in Au +Au at $\sqrt{s_{NN}} = 200$ GeV
- Data: STAR/RHIC Ultra-peripheral AuAu Collision
- Simulation: Sartre
  No t-smearing in Sartre

Slide from J.H. Lee, Analysis: R. Debbe
bSat vs. bNonSat at HERA

$\phi$ – mesons

No distinguishing power!

eRHIC can probe the difference!
Probing the spatial gluon distribution at eRHIC

Amplitude is a Fourier transform from position to momentum space:

\[
\langle A_{T,L}(Q^2, \Delta, x_{IP}) \rangle_{\Omega} = \int \pi r dr dz db (\Psi^* V \Psi)_{T,L}(Q^2, r, z)
\]

\[
J_0([1 - z]r\Delta) J_0(b\Delta) \left( \frac{d\sigma_{q\bar{q}}}{d^2b} \right)_{\Omega} (x_{IP}, r, b)
\]

Cross-section:

\[
\frac{d\sigma}{dt} = \frac{1}{16\pi} \left| \langle A_{T,L}(Q^2, \Delta, x_{IP}) \rangle_{\Omega} \right|^2
\]

Fourier transform again to retain spatial distribution:

\[
F(b) = \frac{1}{2\pi} \int_{0}^{\infty} d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{coherent}}{dt}(\Delta)} \text{ mod }
\]
Probing the spatial gluon distribution at eRHIC

Amplitude is a Fourier transform from position to momentum space:

\[ \langle A_{T,L}(Q^2, \Delta, x_{IP}) \rangle_\Omega = \int \pi rdrdzbd\beta (\Psi^*_V \Psi)_{T,L}(Q^2, r, z) \]

\[ J_0([1 - z]r\Delta)J_0(b\Delta) \]

\[ \frac{d\sigma_{q\bar{q}}}{d^2b} \bigg\rangle_\Omega (x_{IP}, r, b) \]
Away side parton randomized by strong color field

Initial state saturation model

Albacete, Marquet

\[ d + Au \rightarrow \pi^0\pi^0 + X, \sqrt{s} = 200 \text{ GeV}, 2000 < \Sigma Q_{\text{kin}} < 4000 \]
\[ p_{T} > 2 \text{ GeV}/c, 1 \text{ GeV}/c < p_{T} < p_{T_{\mu}} \]
\[ \langle \eta_{c} \rangle = 3.1, \langle \eta_{s} \rangle = 3.2 \]

Preliminary

Corrected Coincidence Probability (rad^2)

\[ \Delta \phi, \sigma \]
\[ 0, 0.48 \pm 0.02 \]
\[ \pi, 1.75 \pm 0.21 \]

Preliminary

Initial and final state multiple scattering

Central

Peripheral

Kang, Vitev, Xing arXiv:1112.6021v1

\[ \langle q^2 \rangle_{dAu} = \langle q^2 \rangle_{pp} + \Delta \langle q^2 \rangle \]

How saturated is the initial state?